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Status of the $B \rightarrow \pi K$ puzzle and its relation to $B_s \rightarrow \phi\pi$ and $B_s \rightarrow \phi\rho$ decays

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Abstract

Some discrepancies between theory and experiment in the $B \rightarrow \pi K$ decays suggest the possibility of a new physics contribution with the structure of an electroweak penguin amplitude. If such a scenario is realised in nature, the branching ratios of the decays $B_s \rightarrow \phi\pi$ and $B_s \rightarrow \phi\rho$ can be enhanced by about one order of magnitude. We review and update the current status of the $B \rightarrow \pi K$ puzzle and its implications for the decays $B_s \rightarrow \phi\pi$ and $B_s \rightarrow \phi\rho$.

1 Status of the $B \rightarrow \pi K$ puzzle

The $B \rightarrow \pi K$ decays provide a useful test of the flavour structure and of CP violation in the Standard Model (SM). They have a small branching ratio, $\mathcal{O}(10^{-6})$, and are sensitive to contributions from New Physics (NP). In the last decade some discrepancies between $B \rightarrow \pi K$ measurements and SM predictions have occurred, leading to speculations of a “ $B \rightarrow \pi K$ puzzle” [2]. The measured values of the branching fractions and CP asymmetries have fluctuated around the SM predictions, giving in some cases discrepancies up to 3σ between theory and experiment, but none of them was large enough and stable over a longer period to provide a clear indication of NP. In Fig. 1 we give an updated comparison of experimental and theoretical results for the $B \rightarrow \pi K$ observables R_i and ΔA_{CP} , which represent ratios of branching fractions

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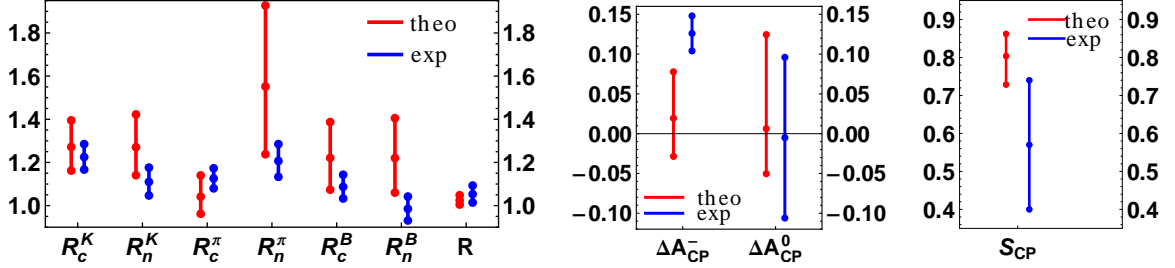


Figure 1: Comparison of theoretical predictions and experimental results for various observables for the $B \rightarrow \pi K$ decays, as defined in [1].

and differences of direct CP asymmetries, as defined in [1]. The results have been obtained employing QCD factorisation (QCDF) [3] for the evaluation of hadronic matrix elements and using the most updated experimental data and theoretical input [4]. The observable which shows the largest discrepancy ($\sim 2.2\sigma$) between theory and experiment is

$$\Delta A_{\text{CP}} \equiv A_{\text{CP}}(B^- \rightarrow \pi^0 K^-) - A_{\text{CP}}(\bar{B}^0 \rightarrow \pi^+ K^-) \stackrel{\text{SM}}{=} 1.9^{+5.8}_{-4.8} \% \stackrel{\text{exp.}}{=} (12.6 \pm 2.2) \%. \quad (1)$$

Referring to [1] for a detailed analysis, we summarise the status of the “ $B \rightarrow \pi K$ puzzle” as follows:

- Direct CP asymmetries arise through the interference of weak and strong phases. They are small ($\leq 10\%$) in the framework of QCDF because strong phases are either perturbative and $\mathcal{O}(\alpha_s)$ -suppressed, or non-perturbative and $\mathcal{O}(\Lambda_{\text{QCD}})$ -suppressed. Therefore it is difficult to explain the experimental result (1) in the SM.
- In the SM, ΔA_{CP} can be topologically parametrised as

$$\Delta A_{\text{CP}} \simeq -2 \text{Im}(r_C) \sin \gamma, \quad (2)$$

where r_C is the colour-suppressed tree-level amplitude, normalised to the dominant QCD penguin amplitude, and γ is the weak CKM phase. A large ΔA_{CP} can be explained only with an enhanced color-suppressed tree amplitude, in contrast with QCDF expectations. Adding, on the other hand, a new isospin-violating amplitude (again normalised to the QCD penguin amplitude)

$$r_{\text{EW}} \rightarrow r_{\text{EW}} + \tilde{r}_{\text{EW}} e^{-i\delta}, \quad r_{\text{EW}}^{\text{C}} \rightarrow r_{\text{EW}}^{\text{C}} + \tilde{r}_{\text{EW}}^{\text{C}} e^{-i\delta}, \quad r_{\text{EW}}^{\text{A}} \rightarrow r_{\text{EW}}^{\text{A}} + \tilde{r}_{\text{EW}}^{\text{A}} e^{-i\delta}, \quad (3)$$

with a new weak phase δ and with the structure of an EW penguin topology (r_{EW} : colour-allowed, r_{EW}^{C} : colour-suppressed, r_{EW}^{A} : annihilation), leads to

$$\Delta A_{\text{CP}} \simeq -2 \text{Im}(r_C) \sin \gamma + 2 \text{Im}(\tilde{r}_{\text{EW}} + \tilde{r}_{\text{EW}}^{\text{A}}) \sin \delta. \quad (4)$$

As a consequence, ΔA_{CP} can turn out much larger in such a scenario than in the SM.

- Theory uncertainties do not allow to extract more information from $B \rightarrow \pi K$ decays alone: The EW penguin and the colour-suppressed tree amplitude always come together in the combination

$$r_{\text{EW}} = r_C e^{-i\gamma}, \quad (5)$$

and ΔA_{CP} , which is the most sensitive observable to this combination, is proportional to its imaginary part, which suffers from the largest uncertainties in QCD. Other observables, such as the ratios R_c^B and R_n^K or as

$$S_{\text{CP}}(\overline{B}^0 \rightarrow \pi^0 \overline{K}^0) \simeq \sin 2\beta + 2\text{Re}(r_C) \cos 2\beta \sin \gamma - 2\text{Re}(\tilde{r}_{\text{EW}} + \tilde{r}_{\text{EW}}^C) \cos 2\beta \sin \delta$$

$$\stackrel{\text{SM, QCD}}{=} 0.80^{+0.06}_{-0.08} \quad \stackrel{\text{exp}}{=} 0.57^{+0.17}_{-0.17}, \quad (6)$$

involve the real part, whose evaluation is on a firmer ground. Still, the EW penguin contribution cannot be disentangled from the dominant QCD penguin and its uncertainties in any of these observables, as they are generated via interference of the two contributions. As an aside, we show in (6) the theoretical vs. experimental prediction for the time-dependent CP asymmetry S_{CP} , and we note that the current value can be accommodated more easily within the NP hypothesis.

In order to gain more insight into the problem, our proposal [1] is to exploit the large variety of non-leptonic B decays into two charmless mesons, with a look in particular at the isospin-violating decays $\overline{B}_s \rightarrow \phi \rho^0$ and $\overline{B}_s \rightarrow \phi \pi^0$, which are dominated by EW penguins, as pointed out for the first time in [5]. We have shown that if NP in this sector exists at a level where it can explain the ΔA_{CP} puzzle, it could be visible in these purely isospin-violating decays. We update here the results with the latest experimental and theoretical input, referring to [1] for a more detailed discussion.

2 The decays $B_s \rightarrow \phi \pi$ and $B_s \rightarrow \phi \rho$

The decays $B_s \rightarrow \phi \pi$ and $B_s \rightarrow \phi \rho$ are purely isospin-violating and their topological structure is very simple. Factorising the dominant EW penguin amplitude, the decay amplitude reads

$$\sqrt{2} A(\overline{B}_s \rightarrow \phi M_2) = P_{\text{EW}}^{M_2} (1 - r_C^{M_2} e^{-i\gamma} + \tilde{r}_{\text{EW}}^{M_2} e^{-i\delta}), \quad (7)$$

where $M_2 = \pi$ or ρ , $r_C^{M_2}$ is the ratio of the color-suppressed tree to the EW penguin amplitude, and $\tilde{r}_{\text{EW}}^{M_2}$ represents a new EW penguin amplitude with a new weak phase

δ . Even though we are facing the same type of EW penguin vs colour-suppressed tree amplitude pollution as in the $B \rightarrow \pi K$ decays, the analysis of $B_s \rightarrow \phi\pi$ and $B_s \rightarrow \phi\rho$ may be interesting:

- A NP amplitude of the order of magnitude needed to solve the ΔA_{CP} problem, i.e. of the same order of the SM EW penguin amplitude, can easily enhance the decays $B_s \rightarrow \phi\pi$ and $B_s \rightarrow \phi\rho$ up to one order of magnitude.
- The branching ratio is proportional to the real part of $r_{\text{C}}^{M_2}$ and $\tilde{r}_{\text{EW}}^{M_2}$, whose evaluation within QCDF is more reliable compared to its imaginary part; moreover, compared to $B \rightarrow \pi K$ observables we avoid additional uncertainties coming from the interference with a QCD penguin amplitude, which is absent in $B_s \rightarrow \phi\pi$ and $B_s \rightarrow \phi\rho$.
- The helicity structure of these B_s decays is different from the one of $B \rightarrow \pi K$ decays, as the former are PV , VV decays, respectively, while the latter are PP decays, with P denoting a pseudoscalar and V denoting a vector meson. The non-perturbative low-energy QCD dynamics is expected to be not correlated among the different classes of decays, and the exact relation cannot be determined within QCDF. A NP contribution is instead of high-energy origin, and its effects can be reliably studied within perturbation theory, allowing for a correlation among the $B \rightarrow \pi K$ and the B_s decays of interest.

3 Model independent analysis

We consider the EW penguin operators

$$\begin{aligned} Q_7 &= (\bar{s}_\alpha b_\alpha)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_\beta q_\beta)_{V+A}, & Q_8 &= (\bar{s}_\alpha b_\beta)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_\beta q_\alpha)_{V+A}, \\ Q_9 &= (\bar{s}_\alpha b_\alpha)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_\beta q_\beta)_{V-A}, & Q_{10} &= (\bar{s}_\alpha b_\beta)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_\beta q_\alpha)_{V-A}, \end{aligned} \quad (8)$$

and we parameterise a NP contribution to the Wilson coefficients as

$$C_{7,9}^{(\prime)\text{NP}}(m_W) = C_9^{\text{LO}}(m_W) q_{7,9}^{(\prime)}, \quad q_{7,9}^{(\prime)} = |q_{7,9}^{(\prime)}| e^{i\phi_{7,9}^{(\prime)}}. \quad (9)$$

Here C_9^{LO} denotes the leading-order SM coefficient and the primed operators are obtained from the SM $Q_{7,9}$ by flipping the chiralities of the quark fields. We perform a χ^2 -fit to determine the NP parameters which best describe the $B \rightarrow \pi K$ data. Further hadronic decays like $B \rightarrow \rho K, \pi K^*, \rho K^*$ are used to impose additional constraints at the 2σ level. The result of the fit is used to study the decays $\bar{B}_s \rightarrow \phi\pi^0, \phi\rho^0$ and to quantify a potential enhancement of their branching fractions. Such an analysis, correlating different hadronic decay modes, is only possible if hadronic matrix elements

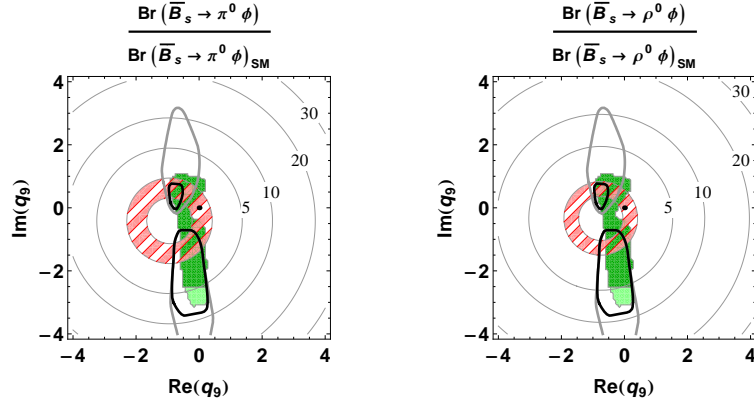


Figure 2: Enhancement factors of the $\overline{B}_s \rightarrow \phi\rho^0, \phi\pi^0$ branching ratios with respect to their SM values. The black dot represents the SM result while the red striped region shows the theoretical uncertainty in the SM. The dark green area is the region allowed by the 2σ constraints from $\overline{B} \rightarrow \pi K^{(*)}, \rho K^{(*)}, \phi K^{(*)}$ and $\overline{B}_s \rightarrow \phi\phi, \overline{K}K$ decays; for comparison, the light green area represents the region allowed by constraints from isospin-sensitive observables only, i.e. the $\overline{B} \rightarrow \pi K, \pi K^{(*)}, \rho K$ decays. The solid black line represents the 1σ CL of the fit with $S_{CP}(\overline{B} \rightarrow \pi\overline{K}^0)$, while the solid grey line represents the 1σ CL of the fit without it. Here we show the scenario $q_9 \neq 0$.

are calculated from first principles like in QCDF because the decays $\overline{B}_s \rightarrow \phi\pi^0, \phi\rho^0$ are not related to any other decay via $SU(3)_F$ symmetries.

From eq. (4) we see that the ΔA_{CP} discrepancy can be solved either through \tilde{r}_{EW} or through \tilde{r}_{EW}^A , which are both induced by the NP coefficients $q_{7,9}^{(\prime)}$. Except for parity-symmetric models (where contributions from primed and unprimed operators exactly cancel), any scenario with at least one of the $q_{7,9}^{(\prime)}$ different from zero can achieve such a solution. The minimal $|q|$ -value needed to reduce the ΔA_{CP} tension below the 1σ level varies among different scenarios. One finds e.g. $|q_7| \gtrsim 0.3$ for a model with only $q_7 \neq 0$, $|q_9| \gtrsim 0.8$ for a model with only $q_9 \neq 0$ and $|q_7| = |q_9| \gtrsim 0.4$ for a model with $q_7 = q_9$ and the primed coefficients being zero. We note however that the solution of the ΔA_{CP} discrepancy via a minimal $|q|$ -value requires a tuning of the phases ϕ_i . Realistic scenarios have larger $|q| \sim 1$ values.

It turns out that the annihilation coefficient $\tilde{r}_{EW,7^{(\prime)}}^A$ induced by $q_7^{(\prime)}$ develops a large imaginary part, so that in scenarios with non-vanishing $q_7^{(\prime)}$ this term gives the dominant contribution to ΔA_{CP} . This explains why in the $q_7 = q_9$ case only a small NP contribution is needed, even though \tilde{r}_{EW} is quite small in this scenario, and it demonstrates the importance of the annihilation term \tilde{r}_{EW}^A .

For the q_7 -only and the q_9 -only scenarios, the result of the fit to $B \rightarrow \pi K$ data and the consequences for the B_s decays of interest are shown in Figs. 2, 3. For details about the fit and the observables used we refer to [1]. We find that the $B \rightarrow \pi K$ and

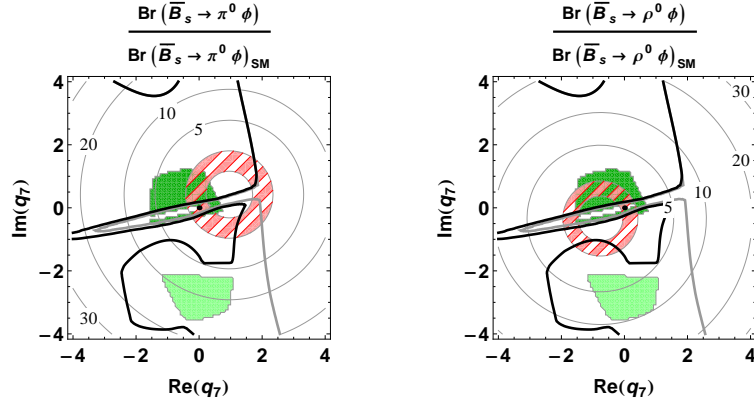


Figure 3: Enhancement factors of the $\overline{B}_s \rightarrow \phi\rho^0, \phi\pi^0$ branching ratios with respect to their SM values. The meaning of the contours and regions is the same as in fig. 2. Here we display the scenario $q_7 \neq 0$. The 1σ region of the fit is the region to the right of the black (grey) curve.

related decays set quite strong constraints on the parameter space. Compared to [1], the most significant update here is the inclusion of the constraints from the full set of branching ratios and CP asymmetries from the $B \rightarrow \rho K^*$ decays, which were not available two years ago. We find that, with inclusion of these decays, the scenarios with $q_7^{(\prime)}$ are now better constrained. Values $|q_i| \gtrsim 5$ ($|q_i| \gtrsim 10$ if only observables sensitive to isospin-violation are taken into account) are ruled out, i.e. NP corrections cannot be much larger than the EW penguins of the SM. The SM point is always excluded at the 2σ level as a direct consequence of the ΔA_{CP} data.

From Figs. 2, 3 the enhancement $\text{Br}^{\text{SM+NP}}/\text{Br}^{\text{SM}}$ of the B_s branching fractions can be read off with respect to the different constraint- and fit-regions. The parts of the allowed region which do not overlap with the SM uncertainty region are those, where one expects to be able to distinguish a NP signal without ambiguity. We find that constraints from other hadronic decays allow in general an enhancement of $\overline{B}_s \rightarrow \phi\pi^0, \phi\rho^0$ by a factor of 5 compared to the SM expectation.

In summary, we see that a measurement of $\overline{B}_s \rightarrow \phi\pi, \phi\rho$ would complement the data from $B \rightarrow \pi K$. On the one hand, one would be able to test the ΔA_{CP} data through an enhancement of the B_s decays, as expected for the $q_7^{(\prime)} \neq 0, q_9^{(\prime)} \neq 0$ scenarios; on the other, we stress that the B_s decays would be useful in order to distinguish among opposite-parity scenarios, which cannot be done with the $B \rightarrow \pi K$ data alone. An analysis of $B \rightarrow \pi K$ should be supported by the analysis of PV decays, suggesting $\overline{B}_s \rightarrow \phi\pi^0$ as an ideal candidate.

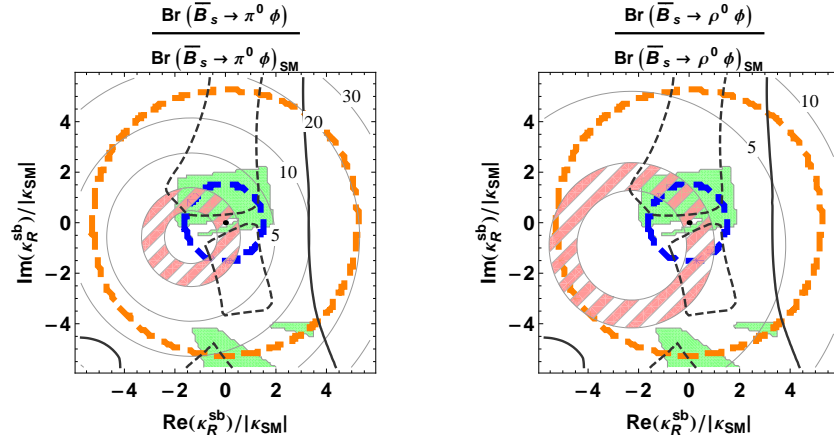


Figure 4: Enhancement factor for the $\overline{B}_s \rightarrow \phi\rho^0, \phi\pi^0$ branching ratios with respect to their SM values in a modified- Z^0 -penguin scenario with right-handed coupling. The green area represents the region allowed by the 2σ constraints from all the considered hadronic decays, while the areas inside the dashed blue line and inside the dashed orange line represent the regions allowed by the 2σ constraint from semi-leptonic decays and from B_s - \overline{B}_s mixing, respectively.

4 Analysis of specific NP models

It is opportune to confront the results obtained with the model independent analysis with the additional constraints which arise when considering concrete NP models. In particular, one has to deal with additional correlations with the semileptonic decay $\overline{B} \rightarrow X_s e^+ e^-$, the radiative decay $\overline{B} \rightarrow X_s \gamma$ and B_s - \overline{B}_s mixing. In [1] we considered three quite general models, a *modified Z^0 -penguin scenario*, a *model with an additional $U(1)'$ gauge symmetry* and the *MSSM*, concluding that the processes above set quite strong constraints and do not allow significant enhancement of the decays $\overline{B}_s \rightarrow \phi\pi, \phi\rho$. Given this result, an updated analysis with the data from the past two years does not change the conclusions. The most significant update concerns B_s - \overline{B}_s mixing, [6], which now points in the direction of the SM, in contrast to the 3.8σ discrepancy at the time of [1]. As a consequence, B_s - \overline{B}_s mixing now supports the results obtained by means of the semileptonic B decay, which gives the strongest constraint and allows at most a factor ≤ 3 enhancement of the decays $\overline{B}_s \rightarrow \phi\pi, \phi\rho$ decays. To give an idea, we provide a plot of the allowed enhancement for the B_s decays in the modified Z^0 -penguin scenario with a non-standard right-handed $s\overline{b}Z^0$ coupling.

5 Conclusion

We have updated our work [1], where we analysed the possibility of probing the $B \rightarrow \pi K$ “puzzle” considering the $\overline{B}_s \rightarrow \phi\pi^0, \phi\rho^0$ decays. The conclusion of [1] is still valid: a solution of the $B \rightarrow \pi K$ discrepancy can be obtained adding a NP contribution to the EW penguin operators, of the same order of magnitude as the leading SM coefficient C_9^{SM} , which in turn gives rise to an enhancement of $\overline{B}_s \rightarrow \phi\pi^0, \phi\rho^0$. Now we get stronger constraints to the possible enhancement from the complete experimental data set of the $B \rightarrow \rho K^*$ decays, and, if a correlation is assumed in a concrete model of NP, from the updated results for B_s - \overline{B}_s mixing. A model independent analysis, where constraints from other non-leptonic B decays are considered, shows that an enhancement of the $\overline{B}_s \rightarrow \phi\pi^0, \phi\rho^0$ decays up to ~ 5 times the SM branching ratio is still possible. In a model dependent analysis, where one needs to take into account constraints from semileptonic B decay and B_s - \overline{B}_s mixing as well, the possible enhancement is reduced to be up to ~ 3 times the SM value. An observation of enhanced $\overline{B}_s \rightarrow \phi\pi^0, \phi\rho^0$ branching ratios would be an interesting complement to the $B \rightarrow \pi K$ data, supporting the picture of NP in the EW penguins.

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